Functional Anatomy of the Ankle

138

Murat Bozkurt, Nihal Apaydin, Safa Gursoy, and R. Shane Tubbs

Contents

M. Bozkurt (✉)
Department of Orthopaedics and Traumatology, Yildirium Beyazit University, Faculty of Medicine, Ankara, Turkey

Department of Orthopedics and Traumatology, Ankara Atatürk Training and Research Hospital, Ankara, Turkey
e-mail: nmbozkurt@yahoo.com; nmbozkurt@gmail.com

N. Apaydin
Department of Anatomy, Ankara University Medicine Faculty, Sihhiye, Ankara, Turkey
e-mail: napaydin@gmail.com

S. Gursoy
Department of Orthopaedics, Ankara Ataturk Training and Research Hospital, Ankara, Turkey
e-mail: safagursoy@yahoo.com

R.S. Tubbs
Pediatric Neurosurgery, Children's Hospital, Birmingham, AL, USA

M.N. Doral, J. Karlsson (eds.), *Sports Injuries*,
DOI 10.1007/978-3-642-36569-0_277

Abstract

The ankle joint is important in human balance and gait, being responsible for transferring the body weight to the foot and performing motions which are essential to gait. Owing to its rigidity, it maintains body balance, and owing to its flexibility, it provides a comfortable, smooth, and nearly effortless human gait. The ankle joint is a synovial hinge joint that is made up of the articulation of three bones, comprising three articulations: the talocrural joint, the subtalar joint, and the distal tibiofibular syndesmosis. Therefore, it is much more than a simple hinge joint because of its unique design. In this chapter the functional and anatomical characteristics of the ankle joint will be discussed.

General Characteristics

Understanding the functional anatomy of the ankle joint is very important since conditions that disturb the normal anatomy can make walking difficult without pain or problems. In addition to this, ankle injuries are among the most common injuries of all musculoskeletal conditions suffered by participants during a variety of physical activities (Fong et al. 2007) and are the most common of all injuries in many sports (Hootman et al. 2007).

The important structures of the ankle joint include:

- Bones and joints
- Ligaments and tendons
- Muscles
- Nerves
- Blood vessels

The ankle, or talocrural joint, is a trochoid synovial joint. It is formed by the articulation of the dome of the talus, the medial malleolus, the tibial plafond, and the lateral malleolus. The lower end of the tibia and its medial malleolus, together with the lateral malleolus of the fibula and inferior transverse tibiofibular ligament, form a deep recess, the so-called mortise for the body of the talus. Thus, some authors call it the "mortise" joint and thought of it as a hinge or ginglymus joint that allows the motions of plantar flexion and dorsiflexion (Floyd and Thompson 2004; Magee 2002). However, several other authors indicate that its axis is more complicated than a simple uniaxial hinge (Barnett and Napier 1952; Hicks 1953; Sammarco et al. 1973; Lundberg 1989; Lundberg et al. 1989a, b). Since the axis of rotation of the talocrural joint passes through the medial and lateral malleoli, it is slightly anterior to the frontal plane as it passes through the tibia but slightly posterior to the frontal plane as it passes through the fibula. It can be considered that the isolated movement of the talocrural joint is primarily in the sagittal plane, although small amounts of transverse and frontal plane motion also occur because of this obliquity of rotation axis (Lundberg et al. 1989a).

The "ankle mortise" is an area rather than a specific anatomical structure. The three articular surfaces of the ankle mortise are:

1. Medial: the lateral portion of the medial malleolus
2. Superior: the tibial plafond
3. Lateral: the medial surface of the lateral malleolus

The mortise contains the superior portion of the talus. This includes a wedge-shaped articular surface, which is also called the trochlea, or dome (Stiehl 1991a; Sarrafian 1993; Cailliet 1997). It is usually more narrow posteriorly than anteriorly (Sammarco and Tablante 1998) (Fig. 1).

The ligaments of the talocrural joint are medial and lateral collateral ligaments. The medial collateral ligament (deltoid ligament) is a strong, triangular band, attached to the apex and the anterior and posterior borders of the medial malleolus. It extends horizontally when the ankle is in anatomical position, running from the anterior edge of the lateral malleolus to the lateral aspect of the neck of the talus (Makhani 1962; Bonnin 1970). It is composed of superficial and deep fibers. The superficial fibers are composed of the anterior (tibionavicular)

Fig. 1 The anatomical structures forming the ankle mortise on a 3T MR image of a healthy male subject

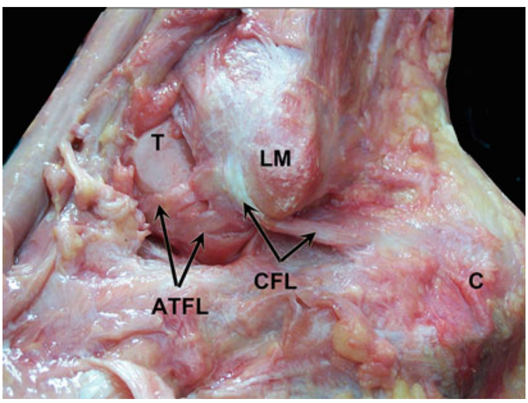

Fig. 2 Lateral view of the ankle joint, left foot. *C* calcaneus, *T* talus, *LM* lateral malleolus, *ATFL* anterior talofibular ligament, *CFL* calcaneofibular ligament

ligament, plantar calcaneonavicular ligament, and posterior tibiotalar ligament. The deep fibers are composed of the anterior tibiotalar ligament, which passes from the tip of the medial malleolus to the non-articular part of the medial talar surface. This ligament is crossed by the tendons of the tibialis posterior and flexor digitorum longus muscles. It is rarely injured alone and, when torn, is commonly associated with a fracture of the distal fibula. Chronic instability of this ligament is a rather rare condition (Standring 2009).

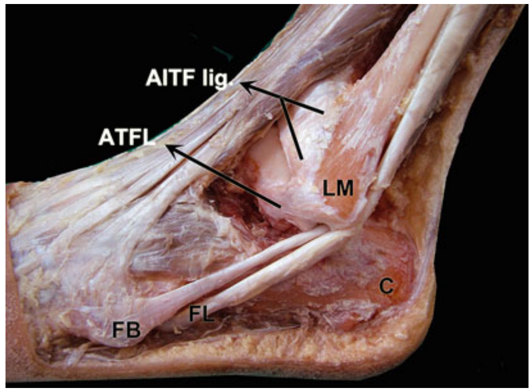

Fig. 3 Lateral view of the ankle joint, left foot. *C* calcaneus, *LM* lateral malleolus, *FB* fibularis brevis, *FL* fibularis longus, *ATFL* anterior talofibular ligament, *AITF lig* anterior inferior tibiofibular ligament

The lateral collateral ligament has also three discrete parts. This ligament complex is composed of the (1) anterior talofibular ligament (ATFL) which extends anteromedially, (2) the posterior talofibular ligament (PTFL) which runs almost horizontally from the lateral malleolus to the posterolateral aspect of the talus having broad insertions onto both the talus and fibula, and (3) the calcaneofibular ligament (CFL) which attaches the distal tip of the lateral malleolus and the lateral tubercle of the calcaneus. The CFL is also crossed by the tendons of the fibularis longus and brevis (Stiehl 1991b; Ferran and Maffulli 2006) (Figs. 2 and 3). The ligament support on the lateral side of the ankle joint is not nearly as strong and is injured most commonly with inversion sprains, often during sports. This is the most commonly injured ligament around ankle region. In these kinds of injuries, the posterior talofibular ligament is almost always spared. Although the resulting increased laxity is tolerated in most cases, surgical reconstruction is sometimes necessary (Anderson and LeCocq 1954; Ferran and Maffulli 2006).

The subtalar joint is a functional unit between the anterior and posterior articular surfaces of the calcaneus and talus and consists of an intricate structure with two separate joint cavities. The posterior articulation is referred to as the talocalcaneal joint and the anterior articulation is regarded as part of the talocalcaneonavicular

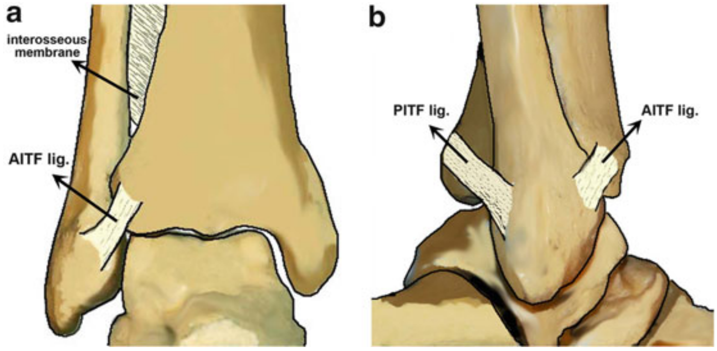

Fig. 4 Tibiofibular syndesmosis (**a**) anterior view; *AITF lig*, anterior inferior tibiofibular ligament (**b**) lateral view; *AITF lig*, anterior inferior tibiofibular ligament; *PITF lig* posterior inferior tibiofibular ligament

joint. It is a modified multiaxial joint and is supported and held in place by the posterior talocalcaneal and interosseous talofibular ligaments, respectively. The subtalar joint allows mainly for inversion and eversion of the foot, and its permitted movements are considered together with those other tarsal joints. With these movements, the subtalar joint allows interaction between the lower leg (internal and external rotation) and the foot (pronation and supination).

The ligaments of the talocalcaneal joint are the lateral, medial, and interosseous talocalcaneal ligaments and the cervical ligament. The lateral talocalcaneal ligament is a short flat fasciculus and is attached anterosuperiorly to the calcaneofibular ligament. The medial talocalcaneal ligament connects the medial talar tubercle to the back of the sustentaculum tali and adjacent medial surface of the calcaneus. The interosseous talocalcaneal ligament is a broad, flat, bilaminar transverse band in the tarsal sinus, and the cervical ligament is just lateral to the tarsal sinus and is attached to the superior calcaneal surface. The ligaments of the talocalcaneonavicular joint are the talonavicular and plantar calcaneonavicular (spring) ligaments. The talonavicular ligament connects the dorsal surfaces of the neck of the talus and the navicular and is covered by extensor tendons. The spring ligament is a broad, thick band connecting the anterior margin of the sustentaculum tali to the plantar surface of the navicular. The dorsal surface of the ligament has a triangular fibrocartilaginous facet on which part of the talar head rests, and its plantar surface is supported by the tendons of tibialis posterior, flexor hallucis longus, and digitorum longus muscles. Its medial border is blended with the anterior superficial fibers of the medial (deltoid) ligament. The calcaneonavicular ligament is the medial band of the bifurcate ligament (Standring 2009).

The distal talofibular syndesmosis is the third joint of the ankle complex between the distal portions of the tibia and fibula. It is a syndesmosis that allows limited movement between these two bones; however, accessory gliding at this joint is crucial to normal mechanics. The articulating parts consist of rough, medial convex surfaces on the distal end of the fibula and the rough concave surface of the fibular notch of the tibia. These surfaces are separated distally for approximately 4 mm by a synovial prolongation from the ankle joint and may be covered by articular cartilage in their lowest parts (Standring 2009). The tibia and fibula are united through the interosseous membrane along the length of the bones and through the anterior interosseous and posterior tibiofibular ligaments distally. The structural integrity of the syndesmosis is necessary to form the stable roof for the mortise of the talocrural joint.

The ligaments of this syndesmosis in addition to the interosseous membrane include the anterior (anteroinferior) tibiofibular (AITF) ligament, posterior (posteroinferior) tibiofibular (PITF) ligament, and interosseous tibiofibular ligament (Fig. 4a, b). The AITF ligament contributes to approximately 35 % of ankle stability; the deep PITF provides 33 %; the interosseous PITF provides 22 %; and the superficial PITF provides 9 %

(Ogilvie-Harris et al. 1994). However, some authors demonstrated that the ligaments of the syndesmosis play a small role in the stability of the ankle as long as the other ligamentous structures are intact (Rasmussen 1985).

The AITF is most commonly injured in conjunction with eversion injuries, and damage results in the so-called high ankle sprain rather than the more common lateral ankle sprain (Miller et al. 1995). The PITF is stronger than the anterior and is on the posterior aspect of the syndesmosis. The ligament projects distal to the bones, in contact with the talus. The interosseous tibiofibular ligament is a continuation of the interosseous membrane and contains many short bands between the rough adjacent tibial and fibular surfaces. It may be the strongest bond between the bones (Standring 2009).

Normal Ligamentous Anatomy and Mechanics

The three major contributors to passive stability of the ankle joint are (1) the congruity of the articular surfaces when the joints are loaded; (2) the static ligamentous restraints mainly by the medial and lateral ligament complexes and the distal tibiofibular ligaments; and (3) the musculotendinous units crossing the joint, which also allow for dynamic stabilization of the joints. The stability increases when leaning forward and decreases when leaning backward by continuous action of the soleus muscle assisted by the gastrocnemius muscle. If backward sway takes the projection of the center of gravity posterior to the transverse axes of the ankle joints, the plantar flexors relax and the dorsiflexors contract. Failure of the fibular muscles can lead progressively to varus instability. However, long-standing failure of the tendon of tibialis posterior, which is relatively common in the elderly female, can result in valgus instability of the ankle and, particularly, a planovalgus foot deformity (Standring 2009).

Around the joint, the fibrous capsule is thin in front and behind. It is attached proximally to the borders of the tibial and malleolar articular surfaces and distally to the talus near the margins of its trochlear surface, except in front where it reaches the dorsum of the talar neck. The capsule is strengthened by strong collateral ligaments. Its posterior part consists mainly of transverse fibers. It blends with the inferior transverse ligament and is thickened laterally where it reaches the fibular malleolar fossa (Standring 2009).

The ankle joint receives its primary support from an array of ligaments that lie medially, laterally, posteriorly, and superiorly to the joint.

Biomechanical Function of Lateral Ligament Complex

In addition to the general anatomy of the ankle, the biomechanical function of each component in stabilizing the joint is worth mentioning. In dorsiflexion, the ATFL is loose, and the CFL is taut. This is reversed in plantar flexion, in which the ATFL is taut, and the CFL is loose. The PTFL is maximally stressed in dorsiflexion.

The CFL is cordlike and is thicker and stronger than the ATFL. The CFL prevents adduction and acts virtually independently in neutral and in dorsiflexed positions.

The ATFL restricts primarily internal rotation of the talus in the mortise; when in plantar flexion, the ATFL also inhibits adduction. From a biomechanical point of view, the ATFL has a lower load to failure than the CFL. The maximum load to failure of the CFL is roughly 2–3.5 times greater than that for the ATFL (Attarian et al. 1985). However, the ATFL can undergo the greatest amount of deformation (strain) before failure and allows for internal rotation of the talus during plantar flexion, in contrast to the CFL and PTFL. Attarian et al. evaluated several ankle bone-ligament-bone in vitro preparations for their capacity to resist force loading and found that the ATFL is the weakest of all the ankle ligaments (Attarian et al. 1985). This suggestion was also corroborated by other authors (Makhani 1962; Bonnin 1970; Attarian et al. 1985; Siegler et al. 1988).

The PTFL is the strongest of the three portions of the lateral ankle. This ligament inhibits external rotation when the ankle is in dorsiflexion. The medial ligaments are the primary restrictors of dorsiflexion, and the PTFL only assists in this function. The short fibers of the PTFL can also restrict internal rotation after the ATFL has been ruptured. If the CFL is disrupted, the PTFL inhibits adduction when the ankle is in dorsiflexion. It is the least commonly sprained of the lateral ankle ligaments (Renstrom and Konradsen 1997).

Biomechanical Function of Medial Complex

The medial ligament complex results in substantial expansion of the medial joint capsule (Bonnin 1970). Biomechanically, the deltoid ligament primarily prevents abduction. After division of both components of the deltoid ligament, anterior instability of the ankle does not increase. If the lateral ligaments are cut, the deltoid ligament acts as a secondary restraint against anterior translation. The fibular ligament primarily inhibits lateral translation of the talus. The deep deltoid ligament provides the greatest restraint against lateral translation. The superficial and deep parts of the deltoid ligament must be completely ruptured in order to tilt the talus in valgus within the mortise.

Siegler et al. and Attarian et al. suggested that the strongest of the main ligaments of the ankle is the anterior and posterior talotibial ligament complex (deep portion of the deltoid) (Attarian et al. 1985; Siegler et al. 1988).

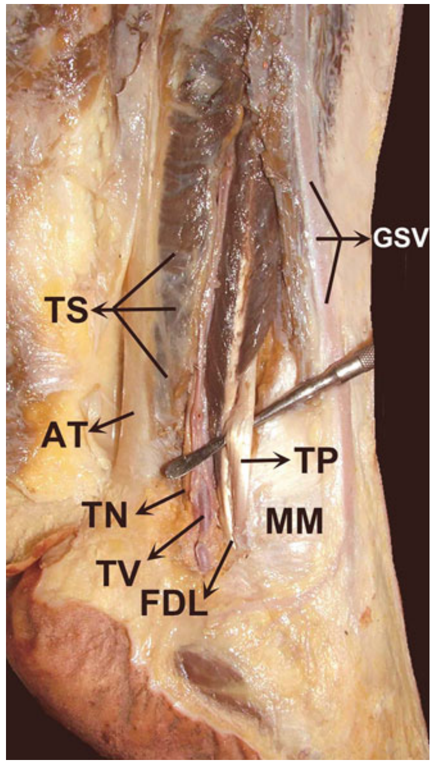

Fig. 5 Medial view of the ankle joint, left foot. *AT* Achilles tendon, *FDL* tendon of flexor digitorum longus, *GSV* great saphenous vein, *MM* medial malleolus, *TN* tibial nerve, *TS* triceps surae (fused gastrocnemius and soleus muscles), *TP* tendon of tibialis posterior, *TV* tibial vessels

Muscles, Tendons, and Nerves

The muscles acting on the foot may be divided into extrinsic and intrinsic groups. Their tendons that cross the ankle allow for the movement of the ankle and stabilize this joint. Distally, the tendons help to stabilize the small joints of the foot. The muscles can be grouped according to their arrangement in the leg. The extensors (tibialis anterior, extensor hallucis longus, extensor digitorum longus, and fibularis tertius) arise in the anterior compartment of the leg, and their tendons pass anterior to the ankle, where they are bound down by the extensor retinacula. The lateral group (fibularis longus and fibularis brevis) arises in the lateral compartment of the leg and their tendons pass posterior to the lateral malleolus, bound down by the fibular retinacula. The flexors arise in the posterior compartment of the leg, and their tendons pass posterior to the ankle, where the tendons of the superficial group of flexors (gastrocnemius and soleus) are inserted into the calcaneus and the tendons of the deep group of flexors (flexor digitorum longus, flexor hallucis longus, and tibialis posterior) are bound down by the flexor retinaculum (Standring 2009) (Figs. 5 and 6).

The intrinsic muscles are contained entirely within the foot and follow the primitive limb pattern of plantar flexors and dorsal extensors. It is customary to group the muscles in four layers, because this is the order in which they are encountered during dissection. However, in clinical practice and in terms of function, the plantar muscles in the foot can be divided into medial, lateral, and

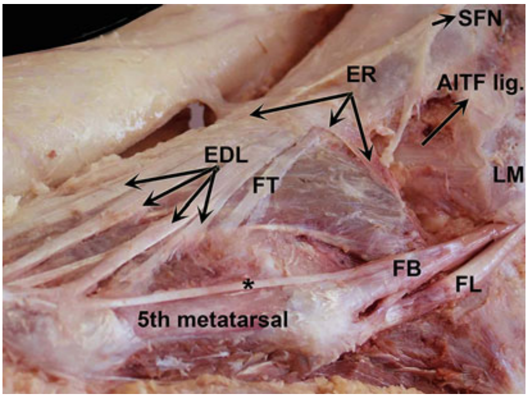

Fig. 6 Lateral view of the ankle joint, left foot. *AITF lig* anterior inferior tibiofibular ligament, *EDL* tendons of extensor digitorum, *ER* extensor retinaculum, *LM* lateral malleolus, *FB* fibularis brevis, *FL* fibularis longus, *FT* fibularis tertius, *accessory tendon from fibularis brevis, *SFN* superficial fibular nerve

intermediate groups. The medial and lateral groups consist of the intrinsic muscles of the great and fifth toes, respectively, and the central or intermediate group includes the lumbricals, interossei, and short digital flexors (Standring 2009).

Calcaneal (Achilles) Tendon

The Achilles tendon (AT) is the thickest and strongest tendon in the human body. It is approximately 15 cm long (11–20 cm) and begins near the middle of the calf fusing with the gastrocnemius muscle proximally. It is broad, flat shape near its origin and receives muscle fibers from soleus almost to its lower end. It gradually becomes more rounded until approximately 4 cm above the calcaneus, below this level it expands and becomes attached to the midpoint of the posterior surface of the calcaneus. The fibers of the calcaneal tendon are not aligned strictly vertically and they display a variable degree of spiraling (Maffulli 1999; Standring 2009).

Vascular Supply

The vascular blood supply of the ankle comes from tarsal and plantar arteries. Superficially, the pulsation of the dorsalis pedis artery is palpable from the midpoint between the malleoli to the proximal end of the first intermetatarsal space. The dorsalis pedis artery gives rise to the tarsal, arcuate, and first dorsal metatarsal arteries. There are two tarsal arteries, lateral and medial. The lateral runs laterally under extensor digitorum. It supplies the extensor digitorum brevis and the tarsal articulations. It makes anastomosis with the branches of the arcuate, anterior lateral malleolar and lateral plantar arteries, and the perforating branch of the fibular artery. The arcuate artery arises near the medial cuneiform; passes laterally over the metatarsal bases, deep to the tendons of the digital extensors; and anastomoses with the lateral tarsal and plantar arteries. It gives rise to the second to fourth dorsal metatarsal arteries. Proximally, in the interosseous spaces, these branches receive proximal perforating branches from the plantar arch. Distally, distal perforating branches from the plantar metatarsal arteries join them. The plantar arch is deeply situated and extends from the fifth metatarsal base to the proximal end of the first interosseous space. It gives off three perforating and four plantar metatarsal branches and numerous branches that supply the skin, fasciae, and muscles in the sole (Standring 2009) (Fig. 7).

The blood supply to the AT is poor and there is deterioration in the nutrition of the tendon with advancing age. The vascular territories of the AT can also be classified simply in three, with the midsection supplied by the peroneal artery and the proximal and distal sections supplied by the posterior tibial artery. Despite the existing discrepancies in the literature, the area of relative avascularity in the mid-substance of the tendon is where the majority of problems occur (Hastad et al. 1959; Jorza and Kannus 1997; Maffulli 1999).

Innervation

The motor and sensory supplies to the ankle complex come from the lumbosacral plexus. The motor supply of the muscles located in the posterior compartment of the leg comes from the tibial nerve (Fig. 7). The anterior compartment muscles are innervated by the deep peroneal nerve, and the lateral compartment muscles by superficial

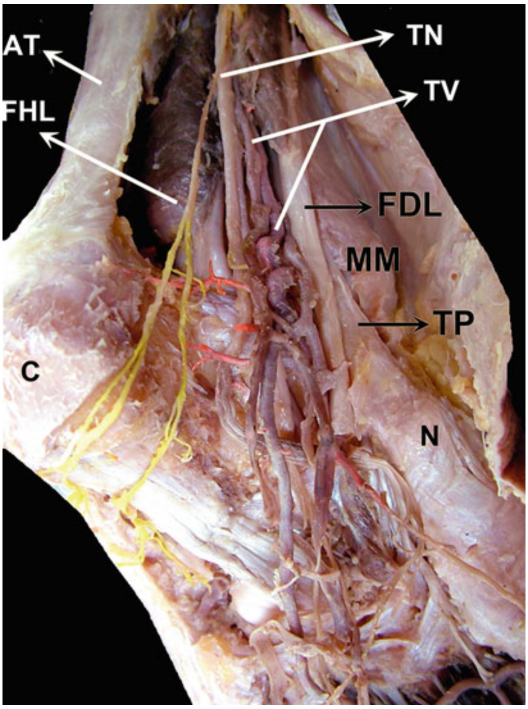

Fig. 7 Neurovascular structures around ankle joint. *AT* Achilles tendon, *C* calcaneus, *FDL* tendon of flexor digitorum longus, *FHL* flexor hallucis longus, *MM* medial malleolus, *N* navicular bone, *TP* tendon of tibialis posterior, *TN* tibial nerve (here it divides into lateral and medial plantar nerves above the level of medial malleolus), *TV* tibial vessels (tibial artery and vein which soon divide into lateral and medial plantar artery and vein)

peroneal nerve. The sensory supply comes from the three nerves (tibial, deep peroneal, and superficial) and two purely sensory nerves: the sural and saphenous nerves. The lateral ligaments and joint capsule of the talocrural and subtalar joints have been shown to be extensively innervated by mechanoreceptors that contribute to proprioception (Hertel 2002; Standring 2009).

All nerves of the foot can be affected by entrapment, leading to a burning sensation in the distribution of that nerve. Tarsal tunnel syndrome is much less common than carpal tunnel syndrome. The compression of the tibial nerve or either of its branches (medial and lateral plantar nerves) can be due to a space-occupying lesion (ganglion) or compression by the overlying flexor retinaculum or a leash of vessels or the deep fascia associated with abductor hallucis. Compression of the first branch of the lateral plantar nerve by the deep fascia of abductor hallucis can lead to heel pain. The medial plantar nerve can be compressed at the "knot of Henry." The knot of Henry is the anatomical landmark where the tendon of flexor hallucis longus crosses deep to the tendon of flexor digitorum longus to reach its medial side in the sole of the foot. The superficial fibular nerve can be damaged in severe inversion injuries of the ankle, and the deep fibular nerve is sometimes compressed by osteophytes in the region of the second tarsometatarsal joint. Sural nerve entrapment is usually secondary to distal fibular trauma and subsequent scar formation around the nerve. Entrapment of the common digital nerve as it passes under the intermetatarsal ligament of the third second webspace can result in a Morton's neuroma, which is probably the most common form of nerve entrapment in the foot (Standring 2009).

Range of Motion

Much confusion surrounds the descriptive terms for movement in the foot and ankle. Plantar flexion and dorsiflexion refer to movements in the sagittal plane. They occur principally, but not exclusively, at the ankle, metatarsophalangeal, and interphalangeal joints. Inversion is tilting of the plantar surface of the foot toward the midline, and eversion is tilting away from the midline in the coronal plane. It takes place principally at the talocalcaneal and transverse tarsal joints. Adduction is movement of the foot toward the midline, while abduction is movement away from the midline in the transverse plane. This movement occurs at the transverse tarsal joints and, to a limited degree, the first tarsometatarsal joint and the metatarsophalangeal joints.

Supination is described as a three-dimensional movement and is a combination of adduction, inversion, and plantar flexion. Pronation is the opposite motion. It can be regarded as a combination of abduction, eversion, and dorsiflexion.

Active movements occur at the ankle, talocalcaneonavicular, and subtalar joints. Movements at the ankle joint are almost entirely restricted to dorsal and plantar flexion. But slight rotation may occur in plantar flexion. The inversion and eversion mainly occur at the talocalcaneonavicular and subtalar joint, and ranges of movement are greater in these joints (Standring 2009).

Normal Ankle Kinematics During Gait

The contraction of tibialis posterior, gastrocnemius, and soleus is the chief factor responsible for propulsion in walking, running, and jumping. Arching of the foot and flexion of the toes enhance the propulsive action of the calf muscles. In walking, the ankle joint is highly loaded up to five times the body weight (Stauffer et al. 1977) although it has a relatively small surface contact area of about 350 mm^2 (Thomas and Daniels 2003). Most of the load is distributed through the superior articular surface of the talus, while the remaining load is transmitted through the talar facets. The medial facet accepts twice the load of the lateral facet (Deland et al. 2000).

The gait cycle is comprised of two stages. In walking, each foot is on the ground (stance phase) for approximately 60 % of the stride and off the ground (swing phase) for approximately 40 %. The knee is straight at heel strike and remains nearly straight for most of the stance phase. The stance phase is further subdivided into five stages. These in chronological order are heel strike (HS), foot flat (FF), mid-stance (MS), heel rise (HR), and toe off (TO) (Rodgers 1988). The swing phase includes the movement of the foot, while the lower limb is propelled forward, from toe off to heel strike. Therefore, it is critical in maintaining normal gait, as it is in this segment of the cycle that the leg must be properly aligned in time for heel strike and in which it must achieve proper height so that the toes clear the floor during forward motion. During the swing phase, the knee flexes to a maximum of 60° at mid-swing (Rodgers 1988; Standring 2009).

The contact area is the largest with the talus in neutral position and in dorsiflexion (Deland et al. 2000). The propulsive forces are transmitted further downward to the foot, and the medial tarsal bones (navicular, cuneiform bones) play an important role in this force transmission.

Walking involves dual-support phases, but in running each foot is on the ground for 40 % (jogging) to 27 % (sprinting) of the stride, so there is an aerial phase, when neither foot is on the ground (Standring 2009). In the act of running, the heel does not touch the ground, but the point of takeoff is still the anterior pillar of the medial longitudinal arch. As the heel leaves the ground, the toes gradually extend.

Conclusion

The ankle joint is not a simple synovial hinge but rather a complex type of joint that is a combination of small bones, tendons, ligaments, and muscles. Understanding the functional anatomy of the ankle joint is very important since conditions that disturb the normal anatomy can make walking difficult without pain or problems.

Cross-References

▶ Chronic Ligament Injuries of the Ankle Joint
▶ Distal Tibiofibular Syndesmotic Disruption (High Ankle Sprain): Missed Injury
▶ Functional Anatomy of the Ankle
▶ Ligamentous Injuries of the Ankle: Sprained Ankle
▶ Syndesmosis Injuries

References

Anderson KJ, LeCocq JF (1954) Operative treatment of the injury to the fibular collateral ligament of the ankle. J Bone Joint Surg Am 36:825–832

Attarian DE, McCrackin HJ, DeVito DP, McElhaney JH, Garrett WE Jr (1985) Biomechanical characteristics of human ankle ligaments. Foot Ankle 6:54–58

Barnett CH, Napier JR (1952) The axis of rotation at the ankle joint in man: its influence upon the form of the talus and the mobility of the fibula. J Anat 86:1–9

Bonnin JG (1970) Injuries to the ankle (facsimile of the 1950 edition. Hafner Publishing, Darien

Cailliet R (1997) Foot and ankle pain, 3rd edn. F.A. Davis, Philadelphia

Deland JT, Morris GD, Sung IH (2000) Biomechanics of the ankle joint. A perspective on total ankle replacement. Foot Ankle Clin 5:747–759

Ferran NA, Maffulli N (2006) Epidemiology of sprains of the lateral ankle ligament complex. Foot Ankle Clin N Am 11:659–662

Floyd RT, Thompson CW (2004) Manual of structural kinesiology, 15th edn. McGraw-Hill, Boston

Fong DT-P, Hong Y, Chan L-K, Yung PS-H, Chan K-M (2007) A systematic review on ankle injury and ankle sprain in sports. Sports Med 37:73–94

Hastad K, Larsson LG, Lindholm A (1959) Clearance of radiosodium after local deposit in the Achilles tendon. Acta Chir Scand 116:251–255

Hertel J (2002) Functional anatomy, pathomechanics, and pathophysiology of lateral ankle instability. J Athl Train 37:364–375

Hicks JH (1953) The mechanics of the foot. I The joints. J Anat 87:345–357

Hootman JM, Dick R, Agel J (2007) Epidemiology of collegiate injuries for 15 sports: summary and recommendations for injury prevention initiatives. J Athl Train 42:311–319

Jorza LG, Kannus P (1997) Human tendons: anatomy, physiology and pathology. Human kinetics, Champaigne

Lundberg A (1989) Kinematics of the ankle and foot: in vivo roentgen stereophotogrammetry. Acta Orthop Scand 60(Suppl 233):1–24

Lundberg A, Goldie I, Kalin B, Selvik G (1989a) Kinematics of the ankle/foot complex: plantar flexion and dorsiflexion. Foot Ankle 9:194–200

Lundberg A, Svensson OK, Nemeth G, Selvik G (1989b) The axis of rotation of the ankle joint. J Bone Joint Surg Br 71:94–99

Maffulli N (1999) Rupture of the Achilles tendon. J Bone Joint Surg Am 81:1019–1036

Magee DJ (2002) Orthopedic physical assessment, 4th edn. Saunders, Philadelphia

Makhani JS (1962) Lacerations of the lateral ligaments of the ankle. J Int Coll Surg 38:454–466

Miller CD, Shelton WR, Barrett GR, Savoie FH, Dukes AD (1995) Deltoid and syndesmosis ligament injury of the ankle without fracture. Am J Sports Med 23:746–750

Ogilvie-Harris DJ, Reed SC, Hedman TP (1994) Disruption of the ankle syndesmosis: biomechanical study of the ligamentous restraints. Arthroscopy 10:558–560

Rasmussen O (1985) Stability of the ankle joint. Analysis of the function and traumatology of the ankle ligaments. Acta Orthop Scand Suppl 211:1–75

Renstrom PAFH, Konradsen L (1997) Ankle ligament injuries. Br J Sports Med 31:11–20

Rodgers M (1988) Dynamic biomechanics of the normal foot and ankle during walking and running. Phys Ther 68:1822–1830

Sammarco GJ, Tablante EB (1998) Foot and ankle in dance. In: Sataloff RT, Brandfonbrener AG, Lederman RJ (eds) Performing arts medicine, 2nd edn. Singular Publishing Group, San Diego, pp 301–320

Sammarco GJ, Burstein AH, Frankel VH (1973) Biomechanics of the ankle: a kinematic study. Orthop Clin North Am 4:75–96

Sarrafian SK (1993) Anatomy of the foot and ankle: descriptive, topographic, functional, 2nd edn. J.B. Lippincott Company, Philadelphia

Siegler S, Block J, Schneck CD (1988) The mechanical characteristics of the collateral ligaments of the human ankle joint. Foot Ankle 8:234–242

Standring S (2009) Gray's anatomy, 40th edn. Churchill Livingstone, Edinburgh

Stauffer RN, Chao EY, Brewster RC (1977) Force and motion analysis of the normal, diseased, and prosthetic ankle joint. Clin Orthop Relat Res 127:189–196

Stiehl JB (1991a) Anthropomorphic studies of the ankle joint. In: Stiehl JB (ed) Inman's Joints of the ankle. Williams and Wilkins, Baltimore, pp 1–6

Stiehl JB (1991b) Biomechanics of the ankle joint. In: Stiehl JB (ed) Inman's joints of the ankle. Williams and Wilkins, Baltimore, pp 39–63

Thomas RH, Daniels TR (2003) Ankle arthritis. J Bone Joint Surg Am 85-A:923–936